An IEEE Standard for Industrial Wireless Performance Evaluation

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***Abstract*—Adoption of wireless systems for use in industrial scenarios is increasing, although slowly, in process control and discrete manufacturing. In particular, factories must make the leap towards wireless networks as a central form of communications to enable certain capabilities outlined by Industry 4.0. Acceptance of wireless as a principal communications mode is slowed by the fact that it is indeed less reliable and less deterministic than its wired counterparts. The industrial wireless medium is susceptible to interference and multi-path fading effects, and their impacts are exacerbated by the mission critical nature of the attached sensing and control applications. Adoption of wireless networks can be made more acceptable if the uncertainty of the wireless medium is better understood and wireless devices are designed to accommodate such uncertainty. This can be achieved through analysis of the RF environment beyond its propagation characteristics and the standardized evaluation of wireless network performance prior to deployment. This article describes the ongoing approach taken by the IEEE P1451.5p working group for the standardization of industrial wireless network performance evaluation. A strategy for modeling channel degradation factors (aggressors) and perspectives on profiling the model for replication of different radio environment scenarios are presented.**

***Index Terms*—industrial wireless networks, factory communications, manufacturing, wireless channels, channel aggressors, IEEE 1451.5p**

I. Industrial Wireless: Challenges and Performance Evaluation

A. Challenges of Adoption

The concept of dedicated wireless networks for use in industrial scenarios began in earnest in the early 2000's with the IEEE 802.15.4 standards and the subsequent industry standards such as WirelessHART, Zigbee, and ISA 100.11a. Other network types arose, which built upon IEEE 802.11 (Wi-Fi) and 802.15.1 (Bluetooth). In addition, proprietary implementations have been developed typically utilizing frequency hopping and time-division strategies to improve performance in the harsh conditions of the factory environments. These wireless systems were almost always designed to operate entirely in the industrial, scientific and medical (ISM) bands of 900 MHz and 2.4 GHz with the 2.4 GHz band being the primary band of use. These early wireless networks were designed for both sensing and actuation, yet industry chose to focus primarily on the sensing aspect for almost two decades, hence information loss has been tolerable. Nevertheless, due to the ubiquity of the ISM bands, the simplicity of the protocols, and the harshness of the industrial wireless channel, transmission reliability of these networks has been poor as compared to wired counterparts. Furthermore, claims of superior connectivity using wireless in the factory has been largely ambiguous as to the circumstances of such claims. Often pristine channel conditions are required to meet performance expectations which is unrealistic and impractical. This approach to evaluating and deploying industrial wireless systems must change if wireless is ever to replace wires in mission critical applications. For example, the multi-path environments of industrial sites in microwave bands can be particularly reflective thereby increasing delay spread, path loss, and Doppler effects [1].

B. Time-sensitive Wireless in Industry 4.0

With the advent of Industry 4.0, wireless networks are envisioned to play a central role in factory and other operational systems communications. The Industry 4.0 vision of the communications system includes concepts such as:

Industrial Internet of Things (IIoT): which extends the internet of things (IoT) to applications found in industrial sectors and applications. The IIoT focuses more intensely on machine-to-machine (M2M) communication and learning to large amounts of data resulting in better enterprise control and operational reliability;

Decentralization of Decisions: in which decisions for optimization and regulation of the industrial process are made closer to the objects performing the work, autonomously, and in real-time;

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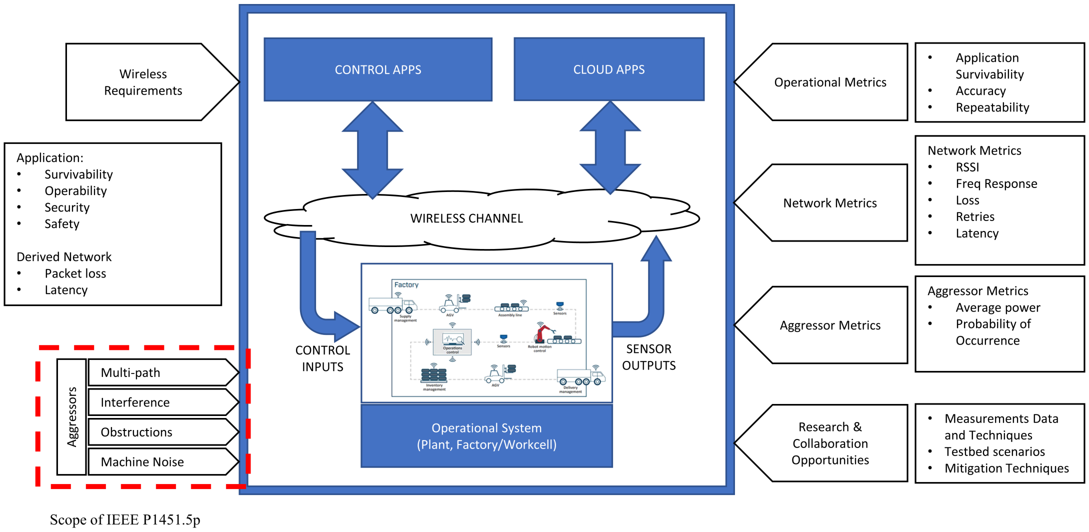

Fig. 1: Scope of the IEEE P1451.5p working group. Considerations, i.e., the channel aggressors, that present an impact to the function of a wireless network are highlighted within the red box. These considerations include propagation phenomena, attenuation, and RF interference.

Improved Mobility: where people, machines, and devices become mobile and reusable across working environments such as an autonomous robot moving from work cell to work cell, receiving instructions, interlocking with other machinery, retooling automatically, and conducting its job safely in the presence of humans;

Pervasive safety systems: where people and machines are protected through high reliability sensing of anomalous events and relaying the event information to an actuation controller within very tight latency requirements;

Digital Augmentation: which are those technological enhancements such as digital twins and augmented reality are used for real-time predictive analysis and support to the human conducting their work thereby improving overall productivity; and

Visualization of Network Performance: which includes technological enhancements that allow for real-time heat mapping of wireless network performance through cloud and centralized management visualization tools. Back-end software tools will peer directly into the physical RF environment to view in real-time the connectivity state conditions including dominant impairment factors at each node in the network.

To make the vision of wireless in Industry 4.0 a reality, wireless networks must become ultra-reliable, have lower and more deterministic latency, and operate with greater resilience. A key technological aspect to this vision is Time-sensitive Networking (TSN) in which access to the communication medium is made more deterministic through gating and scheduling techniques, such as by what has been defined by the TSN Task Group of the IEEE 802.1 Working Group under the harsh and uncertain radio channel found within industrial environments.

C. *Enter the IEEE P1451.5p*

At the wireless mechatronics workshop held online during the International Conference on Factory Communication Systems (WFCS) in June 2021, interference, and jamming were cited by participants in industry as the most concerning issues impeding the adoption of wireless as a primary form of communications within the automation system of a factory workcell [2]. During the workshop, standardized methods for assessing performance of wireless networks used for automation of mechatronic systems prior to commissioning were indicated as essential for the advancement and acceptance of wireless networks if they are to be used for more than sensor applications. Shortly after the workshop, a joint effort between the IEEE Instrumentation and Measurement Society and the IEEE Industrial Electronics Society was proposed, and the new IEEE P1451.5p working group was created within the Instrumentation and Measurement Society Sensor Technology Committee (TC-9) with the purpose to create the Standard for Radio Frequency Channel Specifications for Performance Assessment of Industrial Wireless Systems. The scope of the IEEE P1451.5p working group is shown in Fig. 1.

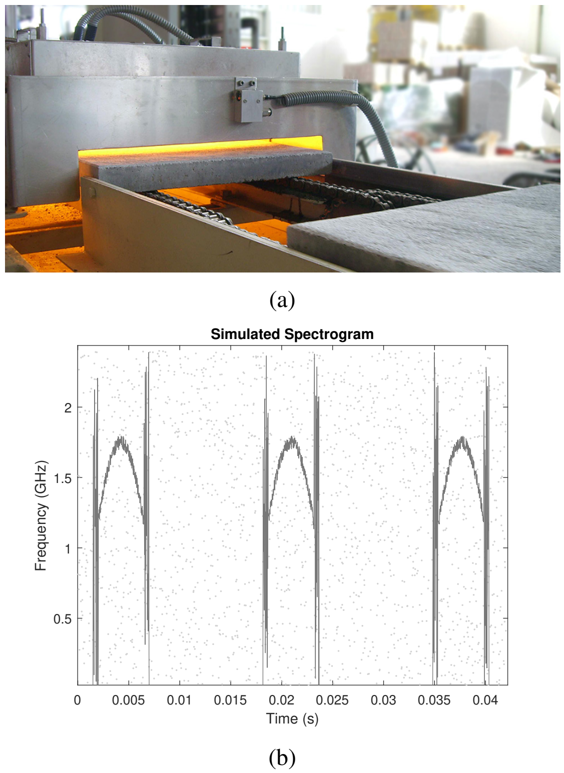

Fig. 2: Examples of non-communications radio interference include aggressors such as in (a) an industrial curing or drying machine emitting high levels of RF energy within the 2.4 GHz ISM radio band Credit: Ceramicx Ltd., Ireland 2022, and (b) microwave ovens (simulated here) [3] both of which can significantly reduce receiver sensitivity.

D. *Practical Issues in Industrial Wireless*

Important to any industrial communications network, wired or wireless, is high reliability and low deterministic latency characteristics. RF impairments, these aggressors, include many factors ranging from radio wave propagation to radiated jamming to environmentally induced interference from vibrations, temperature, and other factors. An example of jamming is shown in Fig. 2 wherein an industrial curing machine found in a roofing materials manufacturing factory emitted high energy RF radio waves into the ambient environment completely blocking communications across the entire 2.4 GHz ISM band. The events would periodically occur throughout the course of a day as the curing machine engaged and disengaged unbeknownst to the factory operation staff. Through careful examination of the spectrum, the cause of the interference was found; however, time and productivity was lost due to poor spectral awareness of this factory environment. A site survey, spectrum monitoring system, or standardized testing approach prior to deployment of the wireless network would have identified this aggressor, and another RF band could have be chosen. Such interference stories are the motivation behind the new standardization effort of IEEE P1451.5p. Developing a standardize approach to testing the industrial wireless network is the main goal of the standard, and spectral awareness is an underlying tenet. A secondary aim of the working group is to compile a database of spectral activity examples at various operational locations to better inform our standard. The database would serve to drive research and development activities in machine learning and test vector generation of interference patterns.

E. *IEEE P1451.5p Road Ahead*

The standard working group has the mandate of making the resulting standard work products agnostic to the communications systems and focus on the RF aggressor definitions. As stated in the working group (WG) charter, the new standard establishes an RF reference environment model with a set of profiles establishing parameters for performance assessment scenarios. The standard will include a model that represents the radio frequency environment and accounts for performance degradation factors (aggressors) that impact radio channel behavior. Individual profiles will be included to address the needs of different industries and levels of severity of the radio channel environment. Performance degradation factors include interference, competing traffic, and multi-path propagation. The new standard is expected to generate research interest in the areas of interference measurement and modeling that will aid in practical replication of aggressors in laboratory settings as well as application of machine learning to the classification of interference types.

Fundamental to creating a model is the process for generation of test vectors used during the performance evaluation process specifically for the data-bearing radio interference. This process is shown in Fig. 3. The process begins with the definition of considered aggressor features and *in situ* measurements of temporal-spectral activity within industrial sites of interest. An aggressor model is defined and trained with available measurement data. The model is used to generate test vectors which will be used for both model tuning and wireless network testing. The remainder of this paper will discuss our initial proposal for the model and subsequent profiles for specific scenarios.

II. Testing and Modeling of Wireless Aggressors

Here, we briefly overview the related standards for assessing the interference impact on a wireless

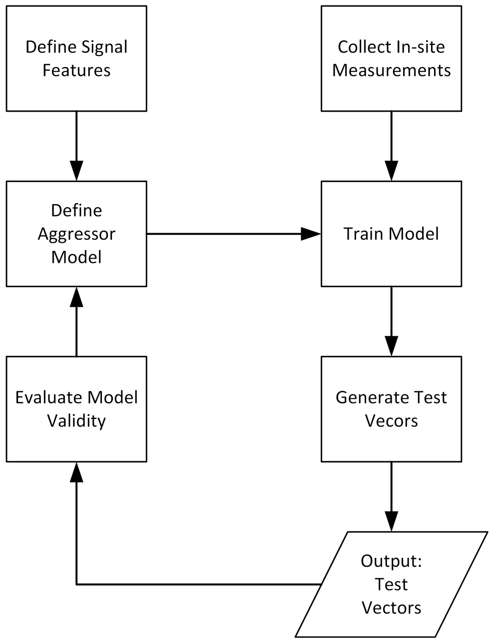

Fig. 3: Concept behind the IEEE P1451.5p test vector generation process for industrial wireless network performance evaluation.

network which include the standards for testing the wireless coexistence impact. However, the large literature of wireless coexistence approaches and their analysis is out of scope of this article. Moreover, we discuss the interference modeling in the literature and its limitations with respect to the requirements of the proposed model of the working group.

The topic of wireless coexistence of various communications protocols and the testing methodologies have been discussed in multiple standardization committees. The coexistence term means the mutual interactions between protocols. However, the testing methodologies may include studying the impact of one network on another when no coordination is performed. Examples of standards that discuss coexistence and testing methodologies include the standards IEEE Std 1900.2-2008, IEEE Std 802.15.2-2003, and IEC 62657-2:2017/AMD1:2019 CSV. Specifically, both IEEE Std 1900.2-2008 and IEEE Std 802.15.2-2003 discuss best practices for coexistence between wireless protocols and reporting and analyzing tools for assessing the coexistence performance. Moreover, the coexistence of industrial networks in TV white space spectrum and its performance evaluation are discussed in IEC 62657-2:2017/AMD1:2019 CSV.

In MIL-STD-461G, the requirements of the Department of Defense (DoD) on various equipment operating under electromagnetic interference (EMI) are defined. These requirements include the susceptibility characteristics of equipment under various testing scenarios including the nature of the tests being radiated or conducted and the types of the emissions. Various scenarios are defined for applicability of corresponding tests. Similarly, in ANSI C63.27-2017, methods for assessing the RF wireless coexistence are described. Key performance indicators (KPIs) are specified to assess the ability of the equipment under test (EUT) to coexist with other equipment in its intended operational environment. Specifically, test plans include the intended and unintended interference signal characteristics such as the frequency band, bandwidth and the wireless protocol. Test plans also include defining the KPIs such as latency, jitter, throughput, error vector magnitude (EVM), non-acknowledgement requests, lost packets, number of retransmissions, and time to complete requests.

Finally, the problem of interference modeling has been discussed widely using various mathematical tools and stochastic models such as in [4] and the references therein. The main goal of the interference analysis is to capture key characteristics of the interference as a function of relatively few parameters. Two main classes of interference modeling can be found, namely, analytical and measurement-based models. Analytical models are generally applied to relatively simple protocols because of the complexities of the models. The second class comprises a set of experimental measurement-based methods. Moreover, modeling can focus on specific features of the aggressors such as power distribution, channel access schemes, temporal correlations, and node location distribution.

III. RF Environment Considerations

Interference to industrial wireless networks in licensed and unlicensed bands can originate from different sources, including man made noise and radios using different communication protocols.

In the sub-GHz band, we can find machinery control signaling, 2$\sim$5G cellular radios, Zigbee radios, and mobile/radio location services. Shot noise can be also found in this band, originated from arc welders, electric motors, and medium-high voltage switches in industrial environments, and from ignition systems in internal combustion engines vehicles [5]. Even though man made noise is typically found in the sub-GHz band, shot noise can leak into adjacent bands, including the 2 GHz band [5].

In the 2 GHz unlicensed band, interference originates mostly from Zigbee, Bluetooth, Wi-Fi, amateur radios and devices such as microwave ovens. Each of the aforementioned protocols have implemented anti-interference mechanisms to

TABLE I: Expected RF Occupants in sub 1 GHz, 2 GHz, 5 GHz and 6 GHz bands

	Frequency	Region	Users
Unlicensed bands	433.05 MHz - 434.79 MHz	R1	Amateur and radiolocation
	902 MHz - 928 MHz	R2	ZigBee WirelessHART ISA 100.11a FIXED, mobile except aeronautical mobile and radiolocation service
	2.4 GHz - 2.5 GHz	WW	Zigbee Bluetooth Fixed mobile, radiolocation, amateur, and amateur satelite service Wi-Fi
	5.170 GHz - 5.730 GHz	WW*	Wi-Fi (DFS), Radar
	5.945 GHz - 7.125 GHz	WW*	Wi-Fi (Wi-Fi 6 and beyond), 5G
Licensed bands	850 MHz, 1900 MHz	R2 (USA)	2G, 3G, 4G and 5G
	1.7 GHz, 2.1GHz	R2 (USA)	4G and 5G
	600 MHz, 700 MHz, 2.3 GHz 2.5 GHz. 3.5 GHz, 5.2 GHz	R2 (USA)	4G and 5G
	3.7 GHz	R2 (USA)	5G

R1: Europe, R2: Americas, WW: Worldwide, WW*: Worldwide (dependent on geographical location)

allow coexistence, including direct sequence spread spectrum, clear channel assessment and frequency hopping among others. Also, 2$\sim$5G cellular radios and signals associated to radio-location systems can also be found in this band.

In addition to 2 GHz bands, Wi-Fi radios can operate in the unlicensed 5 GHz band. Radar signals can be found coexisting with Wi-Fi devices in the high 5 GHz band. Wi-Fi radios must perform dynamic frequency selection (DFS) compliant with FCC 06-96 standard in order to operate in this band. Recently, a 1200 MHz of spectrum in the 6GHz band has been opened for unlicensed use. Wi-Fi is expected to make use of this band after the release of Wi-Fi 6E. No legacy Wi-Fi devices (Wi-Fi 5 and below) are permitted to operate in this band. Finally, 4G and 5G radios can be found in a combination of licensed and unlicensed spectrum ranging from 3.5 to 7 GHz. Table I summarizes the most commonly RF signals found in both licensed and unlicensed bands.

IV. Preliminary Aggressors Model

In order to to build a radio channel aggressors model that can be used to recreate their impact, we mainly focus on the proposed approach to model the interference signals and essential environment impacts in the following. We then introduce a generic finite state Markov chain that can be used to model and generate synthetic aggressors in a controllable fashion to assess the impact of various types of aggressors.

A. Initial Meta-model

Initially, a conceptual model is developed to capture the various components, classifications, and relationships within the aggressor space. We have deployed the Unified Modeling Language (UML) as the descriptive language to present the key ideas and various model components. In the high level class diagram of the meta-model, we classify the aggressor class into two main sub-classes namely the RF aggressors and the physical aggressors. The RF aggressors are defined as any radiating aggressors that may impact the RF band of the network under test. The physical aggressor class captures the impact of the physical environment on the wireless transmissions of the network under test which includes the obstruction and the multi-path effects on the transmitted signals. We further define each of the classes on the high level class diagram by specifying other sub-classes, their various attributes, and the corresponding model parameters.

The meta-model also includes recommendation for the test setup where the use of the model to recreate the test signal is described. Generally, while defining the classes and the corresponding attributes, we keep in mind the practicality of realization such that the used model is computationally efficient and can be replicated with relatively inexpensive equipment.

B. Features of Interference

A wireless communications signal is generally characterized by a wide range of features in the various characterization spaces. However, in order to keep the model usable, we focus on some basic wireless signal features. We consider four main spaces to characterize an aggressor signal, namely, space, time, frequency, and power.

With respect to the space characteristics, we consider the location and the mobility of an interference source. This should have an impact on both the received signal level and environmental impact on the signal. In many cases, the aggressor is a wireless network and not a single source. Hence, the location and the movement of the various sources and their transmissions can be correlated. Another spatial wireless characteristic is the angle pattern of the transmissions including the impact of both the transmit and receive antenna patterns. Temporal features include mainly the above mentioned correlation of transmissions either within a single source's transmissions or a network's transmissions. These correlations can be defined through simple metrics such as the transmission duty cycle and burst metrics such as the coherence time and inter-transmission probability. More complicated temporal correlation distributions can be considered as well.

Frequency features define the varying nature of an aggressor signal in the frequency domain. Initially this include the transmissions frequency band and the signal bandwidth. Both these quantities can be time varying following a probability distribution in many cases. Specifically, frequency hopping signals follow a specific pattern for transmissions. Furthermore, frequency correlation features can be considered such as the coherence bandwidth. The power distribution of the signal can be addressed either from the aggressor's transmit side or at tested network receive side. The transmitted power distribution mainly depends on the communications protocol, the network configurations, and the deployed application. If the received power distribution is considered, we add to these impacts the locations of the communications devices and the surrounding environmental impacts.

C. A Finite-state Markov Chain Model

Correlated data modeling for the purpose of synthetic data generation has been done using Markov models in various applications such as in [6], [7]. Preliminary, we plan to start modelling the wireless RF aggressors data using a finite state Markov chain in order to be computationally efficient in both data modelling and synthetic data generation for aggressor impact assessment.

To briefly describe the initial model parameters and deployment, we define a vector I_n as an interference aggressor vector that contains the values of the various features corresponding to the nth aggressor. Under the assumption of using a finite state Markov chain, each feature can take values in a discrete set within its range. We will use the proposed model for N interference sources that can be transmitting different wireless signals. .

The main task for modelling the interference signals is to evaluate the Markov chain transition probabilities. This task can be performed either through the knowledge of the collected data distribution and hence mathematically evaluating the transition probabilities, or through training the transition probability using interference measurements. In the initialization stage of the model, the number of discrete states of each feature needs to be determined to calculate the total number of the states. Also, the transition time slot of the chain needs to be evaluated in order to capture the required level of transitions of the used synthetic test signals.

We start by choosing a selected set of features in the four main characterization spaces of wireless signals. The considered features will include both the state defining features and the evaluation impacting features. The state defining features are the ones that define each state of the Markov chain. In the initial model, we consider defining the state by the frequency pin, average power value, and the location of the measurement. Inherently, the time pin is captured through the state transition step in the defined Markov chain. On the other hand, the evaluation impacting features are the ones calculated in both the measured data and the replicated data to evaluate the ability of the Markov chain in capturing this set of features. This set of features initially includes the coherence time, the correlation bandwidth, and the power level mean and standard deviation.

The model accuracy is evaluated through comparing the distribution of the synthetic data to the original modeled data with respect to a specific set of features balancing concerns of model accuracy and channel generalization. The communications nature of the network under test should not impact the performance metric of the modeling process.

D. Data Availability and Markov Modeling Examples

The availability of data can be generally limited from industrial environments. As a result, through the course of this standard, the collected data from the collaborators is to be used to build a Markov chain model for synthetic data generation. The plan to collect a large amount of data initially serves two purposes, namely, the accuracy and the robustness of the built model, and capturing various rare scenarios that may happen in different environments.

In the literature, the idea of deploying a Markov chain for data modeling and analysis has been investigated in multiple works such as [8]–[12]. Specifically, in [8], various divergence loss functions are measured to compare the original data and the synthetic data generated by a Markov chain.

It was shown that both the original data sample size and the Markov chain number of states are inversely proportional with the different divergence loss metrics. However, in [12], they are directly proportional with the computation power, and hence, the two quantities need to be optimized.

E. Model Performance Evaluation and Validation

To validate the proposed model, we plan to perform a two-phase evaluation process. First, we evaluate the performance through comparing the characteristics of generated data. Second, we validate the complete process performance through testbed experimentation and on-site wireless network verification. The trained Markov model is planned to be implemented on software defined radios (SDRs) to generate data of similar statistical characteristics to the aggressors' measured data.

To examine the Markov chain model performance, we plan to compare the synthetic data from the model to a validation subset of the actual measured data of the aggressors. Three comparison approaches can be used to evaluate the performance of the Markov chain, namely, population and statistical analysis, clustering-based, and feature-based similarity/divergence analysis [8], [9], [11].

First, in the population analysis, the numbers of produced random instances satisfying a specific feature range are compared to the corresponding number in the measured data. In [11], seven statistical parameters are deployed to perform a Markov model comparison to real measurements of wind speed, namely, the mean, the variance, the transition probability matrix, the probability density, the energy spectral density, the auto-correlation function, and the persistence probability. These measures can be similarly deployed in the comparison of the proposed Markov chain while applying the statistical approach of comparison.

Second, clustering-based model validation is used to measure the similarities between the original and the generated data through studying their topologies. Both sample-based clustering and feature-based clustering can be performed where the data is clustered based on its attributes to be separated on a number of structured clusters [9], [13].

Finally, feature-based similarity/divergence analysis is used to evaluate the performance of the generated data of the Markov chain through a specific set of the aggressors' features. In [8], various divergence losses are defined and evaluated such as the least squared error, the Kullback–Leibler divergence loss, Chi-squared divergence, Hellinger divergence, and Alpha-divergence. Furthermore, other objective functions can be applied over the distance values such as the histogram intersection metric.

Furthermore, the generated aggressor data can be applied to deployed industrial wireless networks in testbeds or realistic industrial scenarios in order to evaluate its impact on the performance of the network under test. In this experimental studies, the controlled aggressors' signals can be applied to clearly measure its impact on both the levels of the wireless network traffic packets and the operational performance of the industrial operations similar to the approach adopted in [14].

V. Profiling and Scenario Modeling

Scenario parameters, such as RF band, locality, other existing networks, as well as details of the physical environment, determine the model profile. Given the model explained in the previous section, parameterization of that model becomes essential. For example, what transmit power, bandwidth, and duty cycle should be specified for each of the aggressors? No one environment or scenario is the same as each geographical location and radio band has a different set of circumstances. These circumstances will determine the values used for each parameter in the model. It is the intention of the IEEE P1451.5p standard to disambiguate the testing of industrial wireless networks prior to deployment. Therefore, a profiling schema for representing the various anticipated scenarios is required for standardization.

Currently, we believe that two viable schema options exist. The first option is an industry-vertical schema in which the type of factory environment is represented. For example, different profiles would be created for factories falling within an industry class such as oil refineries, paper mills, automobile manufacture, warehousing, etc. Each industry is assumed to have radio environment similarities that would lead to a profile being created. However, little measurement research has been done to understand the RF similarities of factory classes, and it may be that each class is too similar to other classes to make industry-specific distinctions. The size of the factories that fall within an industry class could be a determining factor as would its geographical locality.

This leads us to the second schema option which is to organize profiles more generically according to the characteristics of the industrial environment rather than generalization based on any one industry class such as RF band, indoor/outdoor classification, and level of obstructive clutter within the environment. For example, a factory with large machines, welding, and variable speed rotary equipment produces a larger amount of electromagnetic interference; whereas, stockyards and finished good typically produce light reflection and heavy attenuation. Environments with heavy pipe clutter will produce exaggerated multi-path and wave-guide effects, essentially blocking, amplifying, and diffusing transmissions depending on the RF band and locale. These environmentally-based characteristics may be shared among different classes of industry.

This would require the wireless network deployment agency or manufacturer to analyze their factory environment and radio spectrum to determine which profile to select for verification of network performance prior to commissioning. We currently favor this approach for two main reason. First, it may serve as a starting point for a creating generic profile, and, second, the measurement science for a physical environment-based approach would be more easily manageable than attempting to measure in many factories of different classes and then generalizing. Therefore, our short-term goal of adopting this approach is to focus on taking RF activities measurements in sub-7 GHz RF bands as most industrial wireless networks operate below 7 GHz irrespective of the industry class. As the standard grows in adoption, the profiling schema based on industry class, application scenario, mission critically, and other factors may prevail as more measurement data becomes available.

The plan for data replication includes implementing the generated Markov chain in SDRs to generate the corresponding power, frequency, and temporal behavior of the Markov chain. As a result, there will be a number of stored sets of transition probabilities to reflect the various profiles. We plan to parametrize these profiles by various schemas where each profile and its associated Markov chain are annotated by specific properties and feature ranges. For the users of the Markov model, a specific set of the aggressors' features has to be measured/estimated in the environment under test. These numerical parameters will be used in order to associate an environment to a specific profile through feature-distance-based algorithm such as in [15].

VI. Timeline and Challenges

The IEEE P1451.5p standard is proposed to offer standardized methods for assessing the performance of industrial wireless networks in realistic scenarios. Compared to the existing testing and modeling standards for wireless networks in Sec. II, the proposed standard offers testing using measurement-based modeled data and testing profiles based on the industrial use cases, various communications and non-communications based wireless aggressors. These profiles address the needs of different industries and levels of severity of the radio channel environment.

To achieve the IEEE P1451.5p standard goals, the standard WG needs to overcome multiple challenges including modeling the aggressors, adopting an appropriate profile schema, making standard accessible and non-esoteric (i.e. easier to use by industry and those with limited resources), and the reproduction of aggressors with off-the-shelf SDR platforms. In order to overcome the aforementioned challenges, the standard WG members will collaborate where industry and academia are needed to support this effort at various stages of measured data collection, aggressors' modelling, setting up the profiling schema, and the implementation and experimentation of the whole standard process over deployed industrial wireless networks. Generally, aggressor modeling and model evaluation is an open research question that requires using theoretical data modeling tools and realistic measured data from various industrial scenarios. An initial timeline for the standard process is shown in Fig. 4.

Obtaining spectrum measurements from industrial environments can be a challenge due to privacy reasons or the statistical significance of the collected data, especially, in the case of rare interference events. However, because of the importance of obtaining standardized assessment methods, the WG members and their corresponding industrial entities are initially open to share spectrum data. The use of measurement data opens new opportunities to understand sources of aggressor events and understand the realistic situation of the various bands of interest. This newly measured data will be an added value to the currently available troubleshooting data that only explains the scenarios in which deployed wireless networks are impacted by high interference events.

VII. Conclusions and Future Direction

Motivated by the need to deploy highly reliable and deterministic wireless networks to support industrial applications, the IEEE P1451.5p working group was formed. The group intends to develop a standard that recommends methodologies for testing, measuring, and validating RF aggressor profiles within harsh industrial environments. Additionally, the standard will propose a working model that can be used to analyze the impact of RF aggressors on wireless network performance. The working group proposes an industry-wide measurement campaign to measure communications and non-communications generated aggressors within each environmental profile. The group's proposed model will enable many opportunities for research such as

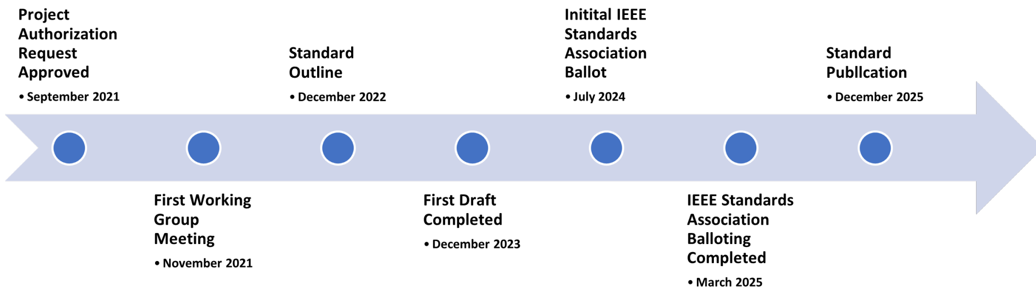

Fig. 4: Timeline of the IEEE P1451.5p Standard

spectral activity measurement campaigns, machine learning for identification of interference types, and techniques for the practical generation of these aggressor for network performance testing. Networks, sensors and nodes can be modeled to develop strategies that mitigate known aggressors within designated environmental profiles.

The potential for wireless technologies in industrial settings may be improved if RF aggressors can be measured, modeled, and countered. "One cannot managed what is not measured." The P1451.5p working group is diversely composed of industrial wireless systems integrators, users, and academics. With industry cooperation to standardize the industrial wireless networks testing methodology, gains in wireless reliability, latency and overall performance can be better achieved bringing the vision of IIoT and Industry 4.0 closer to reality. To learn more and get involved, refer to the IEEE P1451.5P working group here: https://sagroups.ieee.org/p1451-5p.

Acknowledgments

The authors would like to acknowledge the contributions from Iñaki Val, Zhibo Pang, Karl Montgomery, and Kang Lee for helping to capture the underlying ideas and providing feedback on the aggressor model.

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